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Heat transfer enhancement by magnetic nanofluids—A review

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ABSTRACT

Magnetic nanofluids (MNF) constitute a special class of nanofluids that exhibit both magnetic and fluid properties. The interests in the use of MNF as a heat transfer medium stem from a possibility of controlling its flow and heat transfer process *via* an external magnetic field. This review presents recent developments in this field with the aim of identifying major affecting parameters and some novel applications. This review emphasizes on thermal conductivity enhancement and thermomagnetic convection in devices using MNFs as heat transfer media.

Contents

1. Introduction

Dispersion of nano-sized particles of different materials (metals, metal oxides, etc.) in a carrier fluid known as nanofluids has been a subject of intensive investigations over decades due to their potential applications in heat transfer and electronic cooling [1–6]. Magnetic nanofluids (or ferrofluids), which consist of

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colloidal mixtures of *superparamagnetic* nanoparticles suspended in a nonmagnetic carrier fluid, constitute a special class of nanofluids that exhibit both magnetic and fluid properties [7–9]. To prevent the aggregation (due to London-van der Waals interaction and magnetic interaction between the particles), the suspended nanoparticles are coated by a surfactant layer such as oleic acid [10–12], tetramethylammonium hydroxide [13], etc. A wide range of carrier fluids are used, and some magnetic nanofluids are commercially available to satisfy different applications [14]. Theoretically, it should be possible to produce dispersion in any liquid thereby being able to tailor the requirements of viscosity, surface tension, temperature and oxidative stability, vapor pressure, stability in hostile environments [15]. However, the choice of a carrier fluid for MNF suitable for heat transfer applications needs some additional requirements such as high conductivity, high heat capacity, high thermal expansion coefficient, etc. Conventional heat transfer fluid (such as water, oils, ethylene glycol, etc.) could be a superior option for advanced applications. Magnetic nanoparticles used in magnetic nanofluids are usually prepared in different sizes and morphologies from metal materials (ferromagnetic materials) such as iron, cobalt, nickel as well as their oxides (ferrimagnetic materials) such as magnetite (Fe_3O_4), spinel-type ferrites, etc.

MNF has been used as an advanced functional material to position the colloids at a certain part of devices by means of magnetic forces. For this reason, the main aspects for research involve the increase of fluid magnetization, the specific properties of free magnetic nanofluid surfaces in the presence of an external magnetic field and the magnetoviscous and magnetorheological effects [15]. The use of MNF as transfer media becomes of importance in applications [16–18]. In particular, a possibility to induce and control the heat transfer process and fluid flow by means of an external magnetic field opened a window to a spectrum of promising applications including magnetically controlled thermosyphons for technological purposes, enhancement of heat transfer for cooling of high power electric transformers, and magnetically controlled heat transfer in energy conversion systems [15]. The heat transfer enhancement using MNF in the presence of magnetic field can be classified as a compound heat transfer technique with the additives (i.e., magnetic nanoparticles) and an external magnetic field to increase the heat transfer process [19]. Compared to the conventional nanofluids (nonmagnetic nanofluids), the use of MNF affected by external applied magnetic field for heat transfer enhancement offers the following advantages [20]:

a) The possible absence of any moving parts necessary for making the fluid to flow in commonly energy conversion and cooling devices. The current of MNF is generated by temperature difference and non-uniform magnetic field, which can be formed by means of a permanent magnet system. The configuration of this system determines the direction and the type of the fluid flow. As a result, the thermomagnetic convection is readily handled;
b) The thermomagnetic convection is much more intensive than the gravitation one;
c) The possibility of tuning thermophysical properties (thermal conductivity and viscosity) of MNF using external magnetic fields [21,22].

2. Preparation of MNF

MNF is prepared *via* the dispersion of nano-sized superparamagnetic particles into a nonmagnetic carrier fluid such as water, ethylene glycol, hydrocarbon oil, etc. [23]. MNF used in heat transfer applications is subjected to a magnetic field, magnetic field gradient and/or gravitational field, which may contribute to the particle sedimentation in the fluid. Since the interaction range of magnetic nanoparticles in the applied fields is directly related to the particle size/size distribution of magnetic nanoparticles [21], it is obvious that the later plays a vital role in the particle sedimentation, thus affecting the stability of MNF. The stability against the particle sedimentation may be ensured when the thermal energy of the particles becomes greater than that of magnetic and gravitational energies, respectively. the maximum particle size was determined by Odenbach [21] to be $d<(6k_BT/\mu_0M_0\pi H)^{1/3}$ for MNF used in the presence of magnetic field and $d<(k_BT/\Delta\rho gh\pi)^{1/3}$ for MNF in the presence of gravitational field, where k_B, T, M_0, $\Delta\rho$, g, d, H and μ_0 denote the Boltzmann constant, temperature, spontaneous magnetization of the magnetic material, density difference between magnetic particle and the carrier fluid, gravitational acceleration, the height of the sample, the magnetic field and the vacuum permeability, respectively. In addition, the aggregation of magnetic nanoparticles during the synthesis has to be avoided at all costs. In principle, the aggregation of particles increases their active diameter and thus causes a destabilization of the suspension by sedimentation. The maximum particle diameter (d), in this case, was estimated as $d<\left(144k_BT/\mu_0M_0^2\right)^{1/3}$ corresponding to the maximum interaction energy when two interacting particles come into contact [21]. Recent efforts have been made to synthesize metal and metal oxide magnetic nanoparticles with the desired size/size distribution [24]. Metallic nanoparticles such as Ni, Fe and Co were prepared *via* the techniques like simple reduction of metal-salts, gas-phase reduction of metal complexes, thermolysis of metal–polymer complexes, thermal decomposition of metal–carbonyl complexes and submerged arc nanoparticle synthesis system (SANSS) [24,25]. Magnetic nanoparticles of metal oxide such as Fe_3O_4, γ-Fe_2O_3 and spinel-type ferrites of the formula MFe_2O_4 (with M = Mn, Co, Zn, Ni, etc.) are mostly used in MNF due to their chemical stability. Metal oxide magnetic nanoparticles are usually prepared by chemical co-precipitation, micro-emulsion and recently phase transfer [14,24,26].

The use of the required superparamagnetic particles in MNF is not a definitive requirement of magnetic nanofluid stability [8]. A suspension with magnetic nanoparticles in carrier fluids will not be stable due to the presence of London-van der Waals and magnetic forces, leading to the irreversible aggregation of the particles and their subsequent sedimentation. Therefore, the preparation of stable MNF requires an introduction of repulsive forces between magnetic nanoparticles to counteract the London-van der Waals and the dipole–dipole magnetic interactions. The repulsive mechanism between the particles can be achieved, either by coating the particles with a polymer surfactant, which produces an entropic repulsion, and/or by charging the surface of the particles, producing a coulombian repulsion [8,14]. It is interesting to note that the selection of the mechanism to be used should depend mainly on the properties of the carrier fluids and the particles. The dispersion process is usually performed in the presence of a polymer surfactant by ultrasonic equipment and/or a high speed homogenizer.

3. Thermal conductivity of MNF

The original idea of using a suspension for heat transfer application was a possibility of enhancing the thermal conductivity of common heat transfer fluids by the addition of nanoparticles with a higher thermal conductivity [4]. For this reason, some previous investigations on thermal conductivity of nanofluids were dominated by nanofluids prepared with metallic or metallic oxide nanoparticles such as TiO_2, Al_2O_3, Cu, CuO, Ag, carbon

Table 1
Summary of frequently used models for thermal conductivity of MNF.

Model	Expression	Description
Maxwell–Gannet model [70]	$\frac{K_p+2K_f+2\varphi(K_p-K_f)}{K_p+2K_f-\varphi(K_p-K_f)}$	Spherical particles with low volume fraction φ
Modified Maxwell–Gannet model [69]	$\frac{K_i}{K_f}=\frac{K_p+2K_f+2\varphi_i(K_p-K_f)}{K_p+2K_f-\varphi_i(K_p-K_f)}$	Spherical particles with volume fractionφ_i; $i=x,y,z$
Microconvection model [71]	$(1+A\mathrm{Re}^{\gamma}\mathrm{Pr}^{0.003}\varphi)\left[\frac{K_p+2K_f+2\varphi(K_p-K_f)}{K_p+2K_f-\varphi(K_p-K_f)}\right]$	A is a constant, Reand Prare Reynolds and Prandlt numbers respectively, and $\gamma$is a system dependent coefficient.
Bruggeman model [72]	$\frac{K}{K_f}=\frac{1}{4}\left[(3\varphi-1)\frac{K_p}{K_f}+(2-3\varphi)\right]+\frac{K_f}{4}\sqrt{\Delta}$	Spherical particles, with high particle volume fraction φ
	With $\Delta=(3\varphi-1)^2\left(\frac{K_p}{K_f}\right)^2+2(2+9\varphi-9\varphi^2)\left(\frac{K_p}{K_f}\right)$	
Jeffrey model [73]	$\frac{K}{K_f}=1+3\varphi+\varphi^2\left[3\kappa^2+\frac{3\kappa^3}{4}+\frac{9\kappa^3}{16}\left(\frac{\alpha+2}{2\alpha+3}\right)+\frac{3\kappa^4}{64}+\cdots\right]$	High order terms represent pair interaction of randomly dispersed particles
	With $\kappa=\frac{\alpha-1}{\alpha+2}$ and $\alpha=\frac{K_p}{K_f}$	
Rayleigh model [74]	$\frac{K}{K_f}=K_f+3\varphi\frac{K_pK_f}{2K_f+K_p\varphi[1+3.939\varphi^2(K_pK_f)/4K_f+3K_p]K_pK_f}$	Suspensions of spherical particles with a regular particle distribution
Murshed model [75]	$K=\left\{K_f\frac{Q_p\omega(K_p-\omega K_f)(2\gamma_1^3-\gamma^3+1)(K_p+2\omega K_f)\gamma_1^3[Q_p\gamma^3(\omega-1)+1]}{\gamma_1^3(K_p+2\omega K_f)-(K_p-\omega K_f)Q_p(\gamma_1^3-\gamma^3+1)}\right\}+\left\{Q_p^6\gamma^6K_f\left[3\Lambda^2+\frac{3\Lambda^2}{4}+\frac{9\Lambda^3}{16}\left(\frac{K_{cp}+2K_f}{2K_{cp}+3K_f}\right)+\frac{3\Lambda^4}{2^6}\right]\right\}+\left\{\frac{1}{2}\rho_{cp}C_{p-cp}d_s\left[\sqrt{\frac{3k_BT(1-1.5\gamma^3Q_p)}{2\pi_{cp}\gamma^3r_p^3}}+\frac{G_T}{6\pi r_pd_s}\right]\right\}$	Murshed model includes the effects of particle size, nanolayer, particle movements, interactions, and surface chemistry of nanoparticles
	With $\gamma=1+\frac{t}{r_p}$, $\gamma_1=1+\frac{t}{2r_p}$, $\Lambda=\frac{K_{Cp}-K_f}{K_{Cp}+2K_f}$,	$C_{p-p}$and C_{p-f}stand for the specific heat capacity at constant pressure for nanoparticles and carrier fluid, respectively. $G_T$is the total potential energy between two interacting colloidal nanoparticles.
	$K_{Cp}=K_{lr}\frac{2(K_p-K_{lr})+\gamma^3(K_p+2K_{lr})}{(K_{lr}-K_p)+\gamma^3(2K_{lr}+K_p)}$, $\rho_{C_p}$and c_{p-C_p} are density and specific heat of complex particle, respectively, and they are given by $\rho_{cp}=\frac{1}{\gamma^3}\rho_p+\left(1-\frac{1}{\gamma^3}\right)\left\{\frac{3\rho_p}{pb^3}(2t^2+2br_pt+b^2r_p^2)-\frac{3\rho_f}{pb^3}\left[(2+2b+b^2)+br_p(br_p+2bt+t)\right]\right\}$	
	$C_{p-cp}=\frac{1}{\gamma^3}C_{p-p}+\left(1-\frac{1}{\gamma^3}\right)\left\{\frac{3C_{p-p}}{pb'^3}(2t^2+2b'r_pt+b'^2r_p^2)-\frac{3C_{p-f}}{pb'^3}\left[t^2(2+2b'+b'^2)b'r_p(b'r_p+2b't+2t)\right]\right\}$	
	where$p=3r_p^2+3r_pt+t^2$; $b=\ln\left(\frac{\rho_p}{\rho_f}\right)$; $b'=\ln\left(\frac{C_{p-p}}{C_{p-f}}\right)$	

nanotubes [4,27–30]. These affected investigations on thermal conductivity of MNF since common magnetic materials used in MNF have a relatively low thermal conductivity, especially in the absence of external magnetic field. However, recent investigations have proven that a solid material with a high thermal conductivity is not always an effective option for a suspension to enhance the thermal conductivity of a carrier fluid [31]. This finding as well as a possibility of controlling the thermal conductivity of MNF *via* an external magnetic field could be plausible reasons of recent great interests in the enhanced thermal conductivity of MNF. The thermal conductivity enhancement is characterized by a thermal conductivity ratio, which is defined as a quotient of the thermal conductivity of the (magnetic) nanofluid (K) to that of the carrier fluid (K_f).

3.1. *Experimental investigations on thermal conductivity*

Experimental investigations on thermal conductivity of MNF are mostly conducted at room temperature with the common methods for conventional (nonmagnetic) nanofluids [32]. The mostly used techniques for MNF include the transient hot wire [13,33–35] and thermal constants analyzer techniques [22,36,37]. Paul et al. [32] gave the detailed information regarding these two techniques as well as their advantages and disadvantages.

3.1.1. *Thermal conductivity enhancement in the absence of magnetic fields*

Experimental investigations on the thermal conductivity of MNF in the absence of magnetic fields show that the thermal conductivity enhancement is mainly affected by different parameters, i.e., volume fraction of magnetic nanoparticles, particle size/particle size distribution, chemical composition of magnetic nanoparticles, temperature, particle coating layer, etc.

Some work on the effect of particle volume fraction showed that the thermal conductivity of MNF increases with the particle volume fraction [13,22,33,34,37–40]. Abareshi et al. [13] measured the thermal conductivity of a water based magnetite nanofluid as a function of particle volume fraction at different temperatures. The thermal conductivity increased with the increase of the particle volume fraction and temperature. The highest thermal conductivity ratio observed was 11.5% at a particle volume fraction of 3% at 40 °C. Their experimental data showed a fairly good agreement with the simulated results by the Murshed model (see Table 1). Li et al. investigated the effects of particle volume fraction, surfactants and magnetic field on the transport properties of a water based Fe magnetic nanofluid [33]. They observed a thermal conductivity enhancement of MNF with the increase of particle volume fraction both with and without applied magnetic fields. Their results also showed that the viscosity of MNF increased with the particle volume fraction

of the suspended magnetic nanoparticles and the surfactants. Yu et al. [38] investigated the effects of particle volume fraction on the thermal conductivity of a kerosene based Fe_3O_4 magnetic nanofluid prepared *via* a phase-transfer method. The thermal conductivity ratios obtained increased linearly with the increase of volume fraction and temperature and the value was up to 34.0% at 1 vol%. To further investigate the influence of temperature on thermal conductivity enhancement, the measurements were performed in the temperature range from 10 to 60 °C. The results revealed that the absolute thermal conductivity increased with increasing temperature, while the thermal conductivity ratio was almost constant and the thermal conductivities of the MNF tracked those of the carrier fluid. Philip et al. [22,37] conducted a work on thermal conductivity of MNF prepared via the dispersion of magnetite nanoparticles in water, ethylene glycol and kerosene as carrier fluids, respectively. Their results showed that the thermal conductivity ratio increased with the increase of particle volume fraction, but there was no thermal conductivity enhancement for MNF at a volume fraction of < 1.71 vol%. The slope of the linear region was 0.035 and the highest thermal conductivity ratio observed was 23% at 7.8 vol%. Hong et al. [31] investigated the thermal conductivity enhancement of an ethylene glycol Fe based magnetic nanofluid. They found that the thermal conductivity ratio increased nonlinearly with the increase of volume fraction. Hong et al. [39] investigated the thermal conductivity of nanofluids with different volume fractions of Fe nanoparticles in ethylene glycol. Their results confirmed the intensification of thermal conductivity with the particle volume fraction. In the comparison of the copper and iron nanoparticles dispersed in ethylene glycol, the thermal conductivity enhancement in iron-based nanofluids was higher than that in copper-based nanofluid. The observed thermal conductivity enhancement was attributed to the fact that the nanoparticles in the fluids with high volume fractions formed clusters at a higher rate. Zhu et al. [41] prepared a distilled water based Fe_3O_4 magnetic nanofluids and investigated the effect of volume fraction on the thermal conductivity enhancement of the MNF. Gutierrez [34] analyzed the thermal conductivity of water based spinel-type ferrite magnetic nanofluids prepared with magnetic nanoparticles of $Mn_xZn_{(1-x)}Fe_2O_4$ (with $x=0$, 0.3, 0.7, 1). The analysis of the volume fraction dependence on the thermal conductivity showed that the thermal conductivity ratio increased linearly with the increase of volume fraction. In addition, the investigations on the particle composition effects revealed that the thermal conductivity ratio does not depend on the chemical composition of magnetic nanoparticles. The enhancement of thermal conductivity was attributed to the effects of the particle size and the volume fraction of magnetic nanoparticles. The analysis of the carrier fluid effects showed that the thermal conductivity ratio is higher for a carrier fluid with a low thermal conductivity such as common hydrocarbon ($K=0.12-0.14$ W/K m). However, the absolute thermal conductivity of a MNF is higher for a carrier fluid with a high thermal conductivity. For instance, the absolute thermal conductivity for water based magnetic nanofluid ($K=0.801$ W/K m) reported was three times greater than that of oil based one ($K=0.255$ W/K m) for the highest volumetric concentration of both fluids. Holotescu et al. [42] reported on the utilization of the semi-empirical equation for the effective thermal conductivity of the magnetogranulometric analysis to estimate the thermal conductivity of transformer oil based magnetite magnetic nanofluids. In their analysis, the semi-empirical equation for the effective thermal conductivity of the Holotescu–Stoian model [43] was applied, using the results obtained for the size distributions from the magnetogranulometry analysis, followed by a comparison with the measured values of the effective thermal conductivity obtained by a hot ball method. It was revealed that the use of the magnetogranulometric approximation of the magnetite nanoparticle size distribution could evaluate the thermal conductivity more efficiently, compared to the use of the classical Maxwell equation. They also ascertained the importance of the data regarding the analysis of the lognormal distribution by either number or volume, as well as the fact that the results were strongly dependent on the experimental method and the associated model.

3.1.2. *Thermal conductivity enhancement in the presence of magnetic field*

Recent work on the control of the thermal conductivity of MNF has received a particular interest because the "anomalous" thermal conductivity observed under the influence of an external magnetic field. In the presence of magnetic fields, besides the aforementioned parameters affecting the thermal conductivity of MNF without magnetic fields, the thermal conductivity of MNF can be affected by the orientation and the intensity of the applied magnetic field [15,33]. Measurements of thermal conductivity in the presence of magnetic field are usually performed at room temperature using the same techniques as those used in the absence of magnetic fields. The magnetic field is generated by either electromagnets or permanent magnets. Richler et al. [44] investigated the effect of magnetically driven structure formation on heat flux in MNFs on the basis of thermal conductivity measurements in variation of an external magnetic field. For this purpose, they developed an improved measuring device based on the plane heat source instead of the standard hot wire method is used to enable both parallel and perpendicular orientations of magnetic field and heat flux. Thermal conductivity measurements were carried out in variation of strength and direction of an external magnetic field relative to heat flux. It was concluded that unlike former experimental investigations, for the first time the results showed qualitative consistency with theoretical predictions for both orientations.

Li et al. [33] reported on the influence of magnetic field strength and direction on the transport properties of MNF. They found that an external magnetic field had remarkable effects on the both thermal conductivity and viscosity of the MNF. Little change in the thermal conductivity of the MNF was found in the magnetic field perpendicular to the temperature gradient, irrespective of the applied magnetic field strength and the volume fraction of particles. The thermal conductivity of the MNF increased with the strength of the applied magnetic field being parallel to the temperature gradient. The reason for this enhancement was the change of microstructures induced by the external magnetic field in the MNF. They further explained that when the magnetic field was parallel to the temperature gradient, the formed particle chains provided the more effectively bridges for energy transport inside the MNF along the direction of temperature gradient and enhanced the thermal process in the MNF. It was revealed that the viscosity firstly increased with the magnetic field and finally approached a constant as the magnetization of the magnetic fluid achieved a saturation state. This behavior was also explained by the presence of chain-like structures in MNF with respect to the influence of magnetic field. Philip et al. [22,37] reported a dramatic enhancement of the thermal conductivity up to $K/K_f=4.0$ (300%) in magnetite-based nanofluid, under the influence of an applied magnetic field along the direction of heat flow. The reported thermal conductivity enhancement was within the predicted value for parallel mode conduction. The decrease in K observed after the critical value of magnetic field was explained by the "zippering" of chains. They argued that the cluster morphology and distribution both could have impacts on thermal conductivity enhancement and support

the transport of heat through the aggregates. In their report, a magnetically polarizable nanofluid (magnetic nanofluid) could be used as a reversible switchable thermal fluid, i.e., insulation to high thermal conducting fluid and vice versa, by changing the magnetic field. Wright et al. [45] reported an innovative concept of integrating magnetically sensitive metal or metal oxides in a fluid with carbon-nanotubes in order to increase the thermal conductivity of the fluid. It was shown that the MNF with Ni coated single wall nanotubes was significantly enhanced in the presence of magnetic field. The thermal conductivity enhancement observed was attributed to the influence of magnetic field on the microstructure of the fluid. It was indicated that under the applied magnetic field, the Ni coated nanotubes could form aligned chains that favored to connect the nanotubes, resulting in the improved contacts. Wensel et al. [46] investigated the thermal conductivity of nanofluids with metal oxides nanoparticles (Fe_3O_4 and MgO) and carbon nanotubes in the presence of magnetic field. They observed that a maximum thermal conductivity could be increased by up to 10% at a rather low particle weight fraction of 0.02 wt%. The possible explanation to these interesting results was the aggregation of metal oxide particles on the surface of nanotubes by electrostatic attraction and the formation of the chain-structure along the nanotubes. It was suggested that the investigated nanofluids could be used for coolant applications since their viscosity was similar to that of water. Nkurikiyimfura et al. [36] investigated the influences of particle size and particle volume fraction on the thermal conductivity enhancement of an engine oil based magnetite magnetic nanofluid in a magnetic field. It was shown that the thermal conductivity could be enhanced with the smaller magnetite particles used in the nanofluids at a greater particle volume fraction. In addition, the thermal conductivity enhancement was found to be related to magnetic field parallel to temperature gradient. They analyzed that the increase of thermal conductivity ratio was due to the chain-like structures formed in MNF under the influence of magnetic field. The thermal conductivity enhancement observed for the smaller particles was explained by the super-paramagnetic behavior of the smaller particles and their effect on the aggregates formation. Though the magnetic field parallel to temperature gradient exhibited a positive effect on the thermal conductivity of the MNF, a high magnetic field had a negative effect on other thermophysical properties of the fluid such as rheological properties and thermal conductivity itself [22,36,37]. This is due, especially, to the undesirable clumping and zippering of chains under the influence of high magnetic fields. This restriction calls for the simultaneous treatment of thermal conductivity enhancement with other transport properties, especially, the viscosity (η). When the thermal conductivity and magnetoviscous effects were considered, the enhancement could be characterized by a ratio of the thermal conductivity to the viscosity. Philip et al. [47] addressed this issue and suggested the tuning of the K/η-ratio rather than the thermal conductivity alone. Their report devoted to the determination and characterization of the viscosity and thermal conductivity enhancement in a stable magnetic nanofluid with the particles size less than 10 nm as a function of volume fraction, shear rate, magnetic field and time. Their results revealed that, without any magnetic field, the increase of MNF viscosity was much greater than the thermal conductivity enhancement. They also noted that the K/η-ratio of MNF at 0.078 vol% could be tunable from 0.725 to 2.35 by controlling the applied field. The MNF with tunable K/η-ratio could be used as *multifunctional* "*smart materials*" for miniature cooling with damping applications. Gavili et al. [48] conducted experimental investigation on the thermal conductivity of water based MNF under magnetic field created by the Helmholtz coils. The magnetic field strength was controlled by an electric current. The saturation time and the reversibility of thermal conductivity were also examined after the magnetic field was turned off. The obtained results showed that the MNFs with 5.0% volume fraction of nanoparticles with an average diameter of 10 nm enhanced the thermal conductivity more than 200% at maximum value. Furthermore, the variation of thermal conductivity with temperature was also shown.

3.2. Mechanisms of thermal conductivity enhancement and theoretical models

Though the thermal conductivity of MNF has been a subject of some investigations, the mechanisms for interpreting experimental data both in the absence and presence of applied magnetic field are still needed. Among the mechanisms proposed for conventional nanofluids, the Brownian motion and particle clustering/structure are the two much-debated mechanisms [37,49].

3.2.1. Brownian motion

The Brownian motion refers to the seemingly random movement of particles suspended in liquid or gas, and the motion is due to collision with base fluid molecules, which makes particles undergo a random walk motion [3,50,51]. The Brownian motion could contribute to the thermal conductivity enhancement in two ways, namely, the *direct contribution* due to motion of nanoparticles that transports heat (diffusion of nanoparticles) and the *indirect contribution* due to the so called micro-convection of fluid surrounding individual nanoparticles [5,51,52]. It is hypothesized that the later effect could set up a current of heat transfer between nanoparticles and the carrier fluid, hence enhancing the thermal conductivity of the nanofluid. Recent studies rejected this hypothesis, suggesting that the thermal conductivity enhancement of MNF could be explained by the particle clustering [22,37,53]. Philip et al. [22] showed that the microconvection of the fluid medium around randomly moving nanoparticles did not affect the thermal conductivity of a nanofluid and the microconvection model overestimated the thermal conductivity values. They analyzed the modest thermal conductivity enhancement in the well-dispersed particles. The diffusion of magnetic nanoparticles plays an important role at a low volume fraction ($\varphi < 2\%$), which could be explained by the effective medium (Maxwell) theory rather than the effects associated with the Brownian motion induced hydrodynamics. Their explanation to the conductivity enhancement in MNF at a high volume fraction ($\varphi > 2\%$) was due to the presence of dimmers or trimmers in the fluid. These results were in a reasonable agreement with the Maxwell-Gannet model, especially at higher volume fractions.

Tsai et al. [54,55] reported the effect of viscosity on the thermal conductivity of magnetite based nanofluids. They noted that the measured thermal conductivity of nanofluids gradually approached a value predicted by the Maxwell equation with increasing the viscosity. Their results provided an evidence of the viscosity of MNF did affect the thermal conductivity. The diffusion of magnetic nanoparticles could be an important factor that enhanced the thermal conductivity. It was suggested that the thermal conductivity of MNF in the absence of magnetic fields could be predicted by combined models [56–60] where the conduction part could be obtained from the prediction by the Maxwell equations

3.2.2. Nanoparticle clustering

Aggregation of particles into sparse clusters, or ideally into linear chains and its influence on the nanofluids properties have received a particular interest recently, and it is expected to be a

main mechanism of thermal conductivity of the nanofluids [1,2,51,60–64]. The presence of particle clusters in a nanofluid leads to extended and highly conductive paths for the heat flow and thus to a quick heat transport along long distances since heat can be conducted much faster by solid particles if compared to a carrier fluid [60]. Bishop et al. [65] reviewed different interactions occurring in magnetic nanoparticles self-assembly as well as their scales. It was shown that even without the effect of external magnetic field; the magnetic-interaction-induced self-assembled aggregation could occur in MNF. The aggregation structure of magnetic particles controls the heat conduction in the MNF. In the absence of an external magnetic field, the distribution of particles in the MNF is disordered and the thermal conductivity of MNF is isotropic. When magnetic nanoparticles self-assemble, they tend to align their magnetic moments in the direction of the local magnetic field due to the neighboring particles or the applied fields [21,66,67]. This gives rise to the anisotropy of interaction enabling magnetic nanoparticles to form micron-sized, one-dimensional chains/wires, rings, two-dimensional aggregates or even three-dimensional super-lattices. The understanding of the aggregate formation mechanisms, their distribution/distribution morphology and their manipulation with an external magnetic field are prerequisite to understand the mechanisms of thermal conduction in MNF. Hong et al. [39] investigated the effect of magnetic nanoparticles clustering for an ethylene glycol based Fe magnetic nanofluids without magnetic fields. The thermal conductivity was determined as a function of the duration of the application of the ultrasonic vibration, which varied from 0 min (i.e. no vibration applied) to 70 min. It was indicated that thermal conductivity ratio increased with increasing vibration time, and the rate of this increase became smaller for longer vibration time. Furthermore, the variation of thermal conductivity with time after the application of vibration was investigated, and it was found that thermal conductivity decreased with time. Variation of average size of clusters was also determined as a function of time after the application of vibration, and the cluster size increased with time. As a result, the size of the clusters formed by the nanoparticles had a major influence on the thermal conductivity. The effect of particle clustering on the thermal conductivity was also claimed by Zhu et al. [41]. They found that the clustering and nanoparticle alignment was mainly responsible for the anomalous thermal conductivity enhancement. Jiang et al. [68] prepared a MNF by one step phase transfer, and investigated the aggregation effect on thermal conductivity enhancement of the prepared MNF. The microstructure of the MNF was analyzed by a dynamic light scattering method, which unveiled the variation of aggregated configurations with particle concentration and time. The observed wave-like structure of the measured thermal conductivity as a function of particle concentration was explained as the manifestation of the aggregation-structure variation. The analysis for the possible mechanism of aggregate formation in MNF in zero magnetic fields revealed that the particle coating layers were also of importance in the cluster formation. They concluded that the thermal conductivity of MNF could be manipulated for some nanofluids by changing a stabilizer used and thus controlling the structure of the aggregates. Philip et al. [22] performed an experiment to prove the enhanced thermal conduction through percolating structures in MNF. They stated that the maximum enhancement was observed when the chains like aggregates were well-dispersed without clumping. The MNF could be used as a reversible switchable thermal fluid, i.e., insulation to high thermal conductivity and vice versa, *via* the change of the magnetic field.

Some attentions have been paid to theoretical and mathematical modeling of the thermal conductivity enhancement of MNF both in the absence and presence of magnetic fields. Table 1 summarizes the commonly used models to validate experimental results.

Fang et al. [69] attempted to model the thermal conductivity of MNF in the presence of magnetic field. Their model consisted of the modified Maxwell-Gannet model by the introduction of an anisotropic constant that accounted for the microstructure of the fluid under an applied magnetic field.

The obtained model was given as

$$\frac{K_x}{K_f} = \frac{K_p+2K_f+2\varphi_x(K_p-K_f)}{K_p+2K_f-\varphi_x(K_p-K_f)} \tag{1}$$

With $\varphi_x=(1+C_x)\varphi$ where C_x is the anisotropic structure parameter in the x direction expressed as

$$C_x = \frac{1}{N}\sum_{i=1}^{N}\sum_{j>i}C_{ij}^x \tag{2}$$

$$C_{ij}^x = \left[\left(\vec{n}_x\cdot\vec{e}_{ij}\right)^2-\frac{1}{4}\right]\left(\frac{d}{r_{ij}}\right)^3 \tag{3}$$

where subscripts i and j are particle numbers, d is the diameter of the particle, $r_{ij}=r_i-r_j$, $r_{ij}=|\vec{r}_{ij}|$, $\vec{e}_{ij}=\vec{r}_{ij}/r_{ij}$, r_i is the position of the i^{th} particle, $\vec{n}_x$ is the unit vector along the x direction. From Eqs. (2) and (3), the higher particle volume fraction, the shorter distance between two particles $r_{ij}=|\vec{r}_{ij}|$, the greater value of the anisotropic structure parameter C_x could be obtained. When the chain like structure along the x direction becomes more obvious, the value of the anisotropic structure parameter C_x becomes greater. The anisotropic structure parameter C_x well characterizes the distribution of particles along the x direction. Note that the same method can be used to calculate the thermal conductivity of MNF along the y and z directions. The anisotropic thermal conductivity of MNF calculated by the modified Maxwell-Gannet formula is in agreement with those computed by the numerical methods.

Fu et al. [70] conducted theoretical investigation on the effective thermal conductivity tensor for MNFs using a two-step homogenization method. The differential effective medium theory was used to determine the equivalent thermal conductivity of magnetizable nanoparticle chains and then, the theory was generalized to self-consistent anisotropic effective medium theory to investigate the effective thermal conductivity tensors of magnetic nanofluids. The numerical results showed that the aspect ratio of chain-like aggregated clusters plays an important role in enhancement of anisotropic thermal conductivity. In addition, the theoretical results on the elements of thermal conductivity parallel to the fields and perpendicular to the fields were in good agreement with the experimental data. Their results further confirmed the non-monotonic dependence of effective thermal conductivity on magnetic field strength, in accordance with experimental reports.

Nkurikiyimfura et al. [71] investigated the effect of chain-like magnetic nanoparticles aggregates on the thermal conductivity of magnetic nanofluids (MNFs) in magnetic field *via* a proposed model of thermal conductivity of MNFs. The anisotropic feature of thermal conductivity ratio was predicted based on the field induced chain-like magnetic nanoparticles aggregates in MNFs. It was indicated that for a magnetic field parallel to temperature gradient, the thermal conductivity component along the magnetic field was significantly enhanced due to the magnetic field induced chain-like magnetic nanoparticles aggregates. The experimental data of thermal conductivity enhancement along the magnetic field direction were similar to those predicted by the proposed model.

4. Thermomagnetic convection

Thermomagnetic convection refers to a convective heat transfer that makes use of the spatial gradient in the magnetic susceptibility of MNF that is produced in the presence of a temperature gradient [72–74]. When a MNF is exposed to a non-uniform magnetic field in the presence of a temperature field, besides the conventional gravitational body force, the varying susceptibilities result in a non-uniform magnetic body force on the MNF (*Kelvin body force*), given as $\vec{f}_m = \mu_0(\vec{M}\cdot\vec{\nabla})\vec{B}$, where μ_0 stands for the magnetic permeability of the vacuum, and $\vec{M}$ the magnetization and $\vec{B}$ the magnetic induction [75,76]. When the approximation of equilibrium magnetization with magnetic susceptibility is dependent solely on the local value of applied magnetic field and the density, magnetic and gravitational forces both are potential. The *Kelvin body force* creates a static pressure field in the flow that is symmetric about the applied magnetic field producing an irrotational force field. Such a symmetric field does not alter the velocity profile and the convection inside the fluid cannot arise [9]. The non-potentiality of the bulk forces (gravitational and magnetic forces) appears only if a fluid possesses a spatial non-uniformity of the density ρ and magnetization $\vec{M}$ due to their dependences on temperature or on the particle concentration φ [77]. The later condition is satisfied for non-isothermal systems with an asymmetric (or biased) temperature distribution about the imposed magnetic field. The resultant *Kelvin body force*, which is also asymmetric in this case, creates a field force, which leads to the self-organized adjective motion of the MNF across isotherms. The condition for the free convection to develop is calculated as follows [77]:

$$\vec{\nabla}\times\vec{f} = \vec{\nabla}T\times\left[\beta_T\rho_0\vec{g} \pm \mu_0\beta_m\frac{\chi_0(H)}{2}\nabla H^2\right] \neq 0 \tag{4}$$

where $\vec{f}$ denotes the vector sum of the Kelvin body force and the gravitational body force; the sign $\pm$ $\pm$ denotes the parallel and anti-parallel orientation of the magnetic field gradient with respect to the gravitational force, β_m is relative pyromagnetic coefficient of the fluid, and β_T is the relative volumetric expansion coefficient.

The heat transfer intensity is determined by the Rayleigh number *Ra*, which consists of thermomagnetic and thermogravitational parts:

$$Ra = Ra_T + Ra_m = \frac{\rho c_p l^4}{\eta K}\frac{dT}{dz}\left(\beta_T\rho g + \mu_0\beta_m M\frac{dH}{dz}\right) \tag{5}$$

According to the numerical analysis, even in lab-scale experiments, thermal (Ra_T) and magnetic (Ra_m) Rayleigh numbers both are greater; they can exceed the values of 10^5–10^6, showing that the problem of convective heat transfer may be theoretically considered in the framework of a boundary layer approximation [77]. From the expression of the Rayleigh number, it is clear that the intensity of thermomagnetic convection and therefore the efficiency of devices using MNF as heat transfer media is provided not only by the magnetic field and the temperature distributions fields but also by the properties of MNF with the thermophysical properties and the pyromagnetic coefficient, i.e., the degree of dependence of magnetization on temperature. In general, the pyromagnetic coefficient of a MNF is given by [78]

$$\beta = \beta_T M + \left(\frac{\partial M}{\partial m}\right)\left|\frac{dm}{dT}\right| + \left|\frac{\partial M}{\partial T}\right| \tag{6}$$

with

$$\beta_T = -\frac{1}{\rho}\frac{d\rho}{dT}$$

where ρ and β_T denote the density of magnetic liquid and its thermal expansion coefficient, respectively. In high magnetic fields, when magnetization of liquid is close to saturation, the pyromagnetic coefficient can be simplified as

$$\beta = M(\beta_T + \beta_m) \tag{7}$$

where $\beta_m = (1/m)(dm/dt)$ denotes the relative pyromagnetic coefficient of dispersed material. Under these conditions, the value of pyromagnetic coefficient increases with increasing the sum $\beta = (|dm/dT| + \beta_T)$ in the required temperature range for the same MNF. This condition suggests that the choice of magnetic material should depend on the thermal expansion of the carrier fluid. For liquids with small thermal expansion, this coefficient of (dm/dT) is more important. In low magnetic fields, the linear law of magnetization can be assumed and the value of pyromagnetic coefficient is expressed as

$$\beta = M\left(\frac{1}{T} + \beta_T + 2\beta_m\right) \tag{8}$$

It is clear that under low magnetic fields, the share of dispersed material in pyromagnetic coefficient becomes more significant [78]. Recent efforts have been made to synthesize MNF suitable for heat transfer application. A special aspect is to prepare magnetic nanoparticles with a greater pyromagnetic coefficient, i.e., at the Curie temperature being close to the operating range (considering the boiling point of the carrier and the stability of the fluid at elevated temperature). The most used magnetic materials are the Zn-substituted spinel-type ferrites because Zn substitution alters their magnetic parameters in a wide range of values [79–81]. This allows to obtain ferrite particles with different thermomagnetic coefficients. $Mn_{0.5}Zn_{0.5}Fe_2O_4$ based magnetic nanofluids are widely used amongst due to their low Néel temperature (100 °C), and thus higher thermomagnetic coefficients (see Table 2).

4.1. Experimental investigations on thermomagnetic convection

Shuchia et al. [82] investigated the effect of magnetic field position on heat transfer and driving force characteristics of a mixture of MNF with an organic fluid introduced in a heat transport device. Their results indicated that the heat transfer capability and the magnetic driving force were improved by magnetic fields when the magnetic field was applied on the entrance of the heated region. Blums et al. [77] investigated the heat transfer from a nonmagnetic cylinder to a $Mn_xZn_{(1-x)}Fe_2O_4$ tetradecane temperature sensitive magnetic nanofluid, under the influence of transverse laminar free convection in the presence of uniform and non-uniform magnetic fields directed transversally to the axis of the cylinder. Their results confirmed the additive action of thermo-gravitation and thermomagnetic body forces on the heat transfer intensity in ferrofluids. The heat transfer enhancement was attributed to the properties of MNF and the magnetic field gradient. They explained that it was possible to use temperature sensitive magnetic nanofluids to achieve a magnetic Rayleigh number (Ra_m) that exceeds the thermo-gravitational Rayleigh number (Ra_T). They also found that a greater magnetic Rayleigh number and a higher heat transfer could be achieved when the magnetic field gradient was increased. Zablockis et al. [83] conducted experimental and numerical investigations of thermomagnetic convection in a heated cylinder under the magnetic field in a solenoid. They found that the heat transfer under a magnetic field could be increased. However, the solenoid used showed to be impractical, especially for generating sufficiently strong magnetic fields. Yamaguchi et al. [84] conducted an investigation on a Mn–Zn ferrite alkyl-naphthalene based magnetic nanofluid in a cubic cavity. The magnetic field and magnetization were affected by temperature, and the greater magnetization and magnetic forces

Table 2
Summary of theoretical and numerical investigations on thermomagnetic convection.

Author	Geometry and Dimension	Magnetic field	MNF	Model	Remarks
Zablockis et al. [89]	Cylindrical domain dimensions $2 \times 6\ cm$	Non-uniform constant magnetic field of a Solenoid placed in a hollow area inside the domain	Temperature sensitive MNF	Lattice Boltzmann model	The HTC increased up to sevenfold within the studied range of parameters
Yamaguchi et al. [91]	Square cavity	Uniform magnetic field generated by vertical electromagnetic	Alkyl-naphthalene based Mn–Zn ferrite MNF	Lattice Boltzmann model	The HTC increased with the magnetic field strength
Yamaguchi et al. [104]	Partitioned rectangular box		Alkyl-naphthalene based Mn–Zn ferrite MNF	Single model	Heat transfer enhancement is affected by improving heat transfer characteristics at higher Rayleigh number when a strong magnetic field is imposed
Yamaguchi et al. [90]	Cubic cavity	Uniform magnetic field generated by permanent magnets	Mn-Zn ferrite alkyl-naphthalene based MNF	Lattice Boltzmann model	Heat transfer characteristic of the used MNF was enhanced when the magnetic field was applied
Mukhopad-hyay et al. [82]	Two-dimensional enclosure	Magnetic field created by a line dipole	—	Single phase model (scaling analysis)	The Nusselt number scales with $Ra_m^{0.25}$ and thermomagnetic heat transfer increases when the length scale decreases
Zablotsky et al. [96]	Rectangular cell dimensions: $100 \times 15\ mm$ height: $150\ mm$	Permanent magnet attached to the cell	Tetradecane temperature sensitive Mn–Zn based MNF	Single phase model	Thermomagnetic convection exceeds the thermo-gravitational convection; and a higher enhancement is obtained when the magnet is placed near the warmer source
Jafar et al. [105]	Cylinder Dimensions: $3.5 \times 75\ mm$	—	Kerosene based MNF	Mixture (two-phase) model	The heat transfer enhancement is function of magnetic strength and direction. The heat transfer enhancement decreases with the increase of particle size
Jue [106]	2-D square cavity Dimensions: $w=0.05$, $a=3.475\ mm$, $b=3.475\ mm$, $L=5.5\ mm$			Single phase model	The magnetic nanofluid flow and heat transfer are adjusted not only by the magnet strength but also by a proper choice of its position
Strek and Joseph [107]	Channel between two parallel plates Dimensions: $h=0.02\ m$; $L=0.2\ m$	Dipole located below the channel	—	Single model (COSMOL codes)	External magnetic field has influence on both on flow and heat transfer and the convection process is similar to the thermo- gravitational convection
Jafar et al [102]	Cylindrical geometry			Mixture model	The magnetic sorét effect can be higher than the conventional one and its strength depends on the magnetic field magnitude
Xuan et al. [108]	Micro-channel	—		Lattice Boltzmann model	The heat transfer enhancement is related to the orientation magnetic field and a higher enhancement is obtained when the magnetic field gradient is parallel with the incoming stream.

were observed in the regions near the upper wall and center inside the cavity rather than in the region near the bottom and side walls. The analysis of the fluid flow showed a weak flow roll inside cavity under the magnetic force, which brought the lower temperature fluid downward in the center region, and streamed the higher temperature fluid upward along the regions near the side walls. They also found that, with the magnetic field imposed, the heat transfer inside the cavity was increased, compared to that without the magnetic field, and the heat transfer increased further with increasing the strength of the magnetic field. Yamaguchi et al. [85] also performed the numerical and experimental investigations on heat transfer characteristics of a temperature sensitive magnetic nanofluid filled in a cubic container with a heat generating square cylinder stick inside. Their results showed that, regardless of the heat generating object sizes, the heat transfer characteristic of the MNF was enhanced when the magnetic field was applied. However, the heat transfer process became poor as the size of the inside heat generating object increased. This poor heat transfer process was due to the decrease of the space where the fluid flowed with the increase of the heat generating object size. The experimental data were predicted by the numerical result, disclosing the more flow details of the natural convection of the MNF inside cavity.

Some previous work focused on the synergy between the magnetic field and temperature gradient and thermomagnetic convection was analyzed irrespective to the effect of magnetic field on the thermophysical properties of the used MNF. However, recent studies have shown that the thermomagnetic convection can be strongly affected by the externally applied magnetic field through the thermophysical properties of the fluid [86,87]. Engler et al. [86] investigated the magnetoviscous effect on the

thermomagnetic convection. Under certain circumstances, the magnetoviscous effect can affect the thermomagnetic convection. The increase of magnetoviscous effect was attributed to the presence of coarse particles in the studied samples. It was concluded that for the thermomagnetic convection, the magnetoviscous effect could be increased in the MNF, which would affect the experimental results of the threshold of convection. The influence of magnetoviscous effects on the thermomagnetic convection was also confirmed in a recent theoretical investigation on the onset of Bérnard–Mangaroni thermomagnetic convection in a horizontal magnetic nanofluid layer by Nanjundappa et al. [88]. Also, Lajvardi et al. [89] addressed the forced thermomagnetic convection heat transfer of a water based magnetic nanofluid with nanoparticles of Fe_3O_4 (10-nm) in a heated copper tube for laminar flow. They observed a significant enhancement in heat transfer coefficient under the influence of an applied magnetic field and magnetic nanoparticle volume fraction. The observed heat transfer enhancement was attributed to the thermophysical properties of MNF such as thermal conductivity or heat capacity under the applied magnetic field.

4.2. Mathematical modeling and simulation

Several numerical investigations have been conducted on different geometries such as the Rayleigh–Bernard configuration, rectangular enclosure, cylinder, cube, partitioned cavity, etc. [90,91]. The heat transfer processes and fluid flow in these geometries have been simulated in the presence of static magnetic field and more recently in modulated magnetic fields. The commonly used mathematic models can be summarized in two categories:

1. *Single phase (homogeneous) model*. MNF is a multiphase mixture of magnetic nanoparticles and carrier fluid. However, due to the restricted magnetic nanoparticle size, the assumptions of thermal equilibrium conditions and negligible motion slip between particles, MNF is usually considered as a conventional single phase fluid with average physical properties of individual phase that exhibit magnetic behavior. In this case, the conventional hydrodynamic equations can be modified to account for the Kelvin body force, *the so called ferro-hydrodynamic equations*, and coupled with magnetization equation and Maxwell's equations used to model and characterize the fluid flow and heat transfer processes. Mahmoudi et al. [92] analyzed the natural convection for a two-dimensional triangular enclosure with partially heated from below and cold inclined wall filled with nanofluid in presence of magnetic field. The governing equations were solved by a finite volume method. The flow pattern, isotherms and average Nusselt number were presented for $0<Ha<100$, $10^4<Ra<10^7$, $0<\varphi<0.05$ and six cases that were made by location of heat sources. The results showed that in presence of magnetic field the flow field was suppressed and heat transfer decreased. Furthermore, it was observed that a maximum reduction of average Nusselt number in a high value of Ha occurred when $Ra=10^6$. It was found that the nanoparticles were more effective when $Ra=10^4$ where conduction was more pronounced. Sheikholeslami et al. [93] investigated the natural convection in a concentric annulus between a cold outer square and heated inner circular cylinders in the presence of static radial magnetic field using the lattice Boltzmann method. The inner and outer cylinders were maintained at constant uniform temperatures, and it was assumed that all walls could insulate the magnetic field. The numerical investigation was carried out for different governing parameters, i.e., the Hartmann number, nanoparticles volume fraction and the Rayleigh number. The effective thermal conductivity and viscosity of nanofluids were calculated using the Maxwell-Garnetts (M-G) and Brinkman models, respectively. Also, the multi-distribution-function (MDF) model was used for the uniform magnetic field effects simulation. The results revealed that the average Nusselt number was an increasing function of nanoparticle volume fraction as well as the Rayleigh number, while it was a decreasing function of the Hartmann number.
2. *Mixture model* (*two-phase model*). The mixture model uses a single fluid approach, and it is an intermediate between the single phase approximation and full set of equations governing the dynamic of multiphase flow [94]. For this reason, some factors such as friction between magnetic nanoparticles and the carrier fluid, the Brownian diffusion, sedimentation and dispersion are included in the model. The inclusion of the later factors in the model provides a possibility of understanding the function of each phase in the heat transfer process and the problem related to the stability of MNF under both magnetic and gravitational forces [95,96].

Mousavi [97] used CFD techniques to investigate the effects of single phase approximation and mixture model on the flow behavior and heat transfer of a kerosene based magnetic nanofluid in a cylindrical geometry. It was found that at a great particle volume fraction, the mixture model approach is more effective than single phase approach, and the former approach is convenient to study the effects of aggregation and particle size on hydrodynamics of the system. Using the mixture model, they obtained that with coarse magnetic particles, the heat transfer could decrease and the Rayleigh rolls would not be observed.

Xuan et al. [98] investigated the flow and thermal processes of MNF flowing through a micro-channel. By altering the orientation and magnitude of an external magnetic field, they could control the flow and thermal processes of MNF. They also found that the effect of the external magnetic field intensity was dependent upon its magnitude, its synergistic relation with the flow direction of the main stream, the temperature gradient, and gravity in the gravitational field. They concluded that for the purpose of heat transfer enhancement, the most remarkable effect could be achieved when the orientation of the magnetic field gradient is parallel with the incoming stream. They analyzed that a magnetic field gradient opposite to the main stream would suppress a heat exchange between the MNF and the solid surface. Jafari et al. [99] used the mixture model to simulate the heat transfer phenomena in a kerosene based magnetic nanofluid flowing in a cylindrical geometry. It was indicated that the increase of magnetic nanoparticle size could cause the generation of colloids in the system, which had a detrimental effect on the heat transfer of the system. Jafari et al. [96] investigated the parameter effects on the thermomagnetic convection using the Taguchi technique. The thermomagnetic convection in a cylindrical geometry depended on some parameters like the particle diameter, particle volume fraction, temperature difference in the magnetic nanofluid layer, the magnetic field magnitude parallel to temperature gradient and the aspect ratio of the geometry as well. They reported that the magnetic sorét effect could be greater than the conventional one and its strength depended on the magnetic field strength. Their results were in agreement with the experimental data by Volker et al. [100]. Aminfar et al. [101] used the two phase mixture model and the control volume technique to investigate the hydro-thermal characteristics of water based magnetite nanofluid contained in a vertical rectangular duct. The duct was exposed to a non-uniform transverse magnetic field generated by an electric current going through a wire located parallelly under the duct. The results showed that the use of the aforementioned magnetic field increases the Nusselt number and friction factor and also creates a pair of vortices that enhances heat transfer and

Table 3
Existing thermomagnetic convection heat transfer correlations.

Reference	Geometry	Correlations
Ashouri et al. [113]	Square cavity	$\overline{Nu} = 0.03064 \frac{G^{*-0.1101} W^{*0.5868(1+2.314W^{*})}}{1-1.570L^{*}+0.8480L^{*2}} T_r^{0.2278} \times \Pr^{0.01818/(\Pr-0.5)} (a_1 a_2 \eta^{a_3(1-a_4\eta)} Ra_m^{a_5}$
Mukhopadhyay [82]	Rectangular cavity	$Nu \sim \frac{hD}{K} \sim \frac{D}{\delta_T} \sim Ra_m^{0.25}$
Moraveji and Hejazian [114]	Horizontal tube	$Nu = 0.00248\mathrm{Re}^{1.03}\Pr^{0.5}(1+\varphi)^{47.5}$

Nu: Nuselt number, $\overline{Nu}$: overall Nuselt number, h: the heat transfer coefficient (HTC), a_1 and a_2 are the constants.

prevents sedimentation of nano-particles. Furthermore, unlike the axial non-uniform magnetic field, the increase of the Nusselt number for the transverse magnetic field was considerable in all lengths along the duct, and it was also concluded that with increasing the Reynolds number, the effect of the transverse non-uniform magnetic field on the Nusselt number was more than that of the axial non-uniform magnetic field. Suslov [91] investigated the linear stability of MNF between two vertical differentially heated plates placed in a uniform external magnetic field perpendicular to the plates and presented a complete stability diagram for two and three-dimensional disturbances. It was shown that the thermogravitational and magnetic effects were the two mechanisms of appearance of three stability modes. A work with the later modes showed that, depending on the governing parameters, the instability patterns were vertical stationary magneto- convection rolls and/or vertical or obliquely counter-propagating thermogravitational or thermomagnetic waves [102]. Suslov et al. [102] used the disturbance energy analysis to highlight the physical mechanisms driving convection in MNF. They found that the increase of magnetic effect was manifested by the existence of thermomagnetic waves, which gradually replaced thermogravitational buoyance-driven waves. Krakov et al. [103] investigated the influence of porous media and uniform magnetic field on the thermal convection in magnetic fluid. In porous square cavity, the competition between gravity convection and thermomagnetic convection mechanisms could lead to a complicated dependence of the heat flux through the cavity in magnetic field. The increase of magnetic field could enhance and depress heat transfer. It was also indicated that the dependence of the Nuselt number on the Rayleigh number could be complicated, leading to a hysteresis in some cases. Ashouri et al. [104] analyzed the thermomagnetic convection heat transfer in a two-dimensional square cavity by a semi-implicit finite volume method. In their investigation, the side walls of the cavity were heated at different temperatures, the top and bottom walls were isolated, and a permanent magnet was located near the bottom wall. They noted that in the absence of magnetic field, the heat transfer was only affected by conduction. However, the convective flow and heat transfer increased with increasing magnetic field intensity when a magnetic field was applied. Based on the numerical analysis, they introduced a general correlation for the overall Nusselt number on the side walls in a wide range of effective parameters, viz. $1 < \Pr < 10^3$, $2 \times 10^6 < Ra_m < 10^{11}$, $0 < Ma < 10^2$, $0 < \eta < 10^2$, $0 < Tr < 0.3$, $0.25 < L^* < 1.0$, $0 < W^* < 0.1$, $0.02 < G^* < 0.1$, where Pr is the Prandlt number, Ra_m the magnetic Rayleigh number, Ma the thermomagnetic number, η the viscosity, Tr the rational temperature, G^* the gap between the surface of permanent magnet and cavity in dimensionless form, L^*, W^* denote the length and width of the permanent magnet in dimensionless form respectively (see Table 3). The maximum error produced *via* this correlation was approximately 6%. Moraveji et al. [105] presented the computational fluid dynamics (CFD) method, with a single phase approach, to determine the effects of nanoparticle concentration and flow rate on the convective heat transfer and friction factor of water based magnetite nanofluid flowing through a plain copper tube in turbulent regime with different Reynolds numbers ($3000 < Re < 22000$). Magnetite nanoparticles with the average diameter of 36 nm, suspended in water as a base fluid with four particle concentrations of 0.02, 0.1, 0.6 vol% were used. Applying the modeling results, they found two relations to estimate the Nusselt number and friction factor, based on the dimensionless numbers. The results showed that the modeling data were in good agreement with the experimental data. The maximum error was around 10%.

Recent studies analyzed the thermomagnetic convection in the presence of modulated magnetic field [106–108]. Kaloni et al. [107] performed a theoretical investigation of the convective instability problem in the thin horizontal layer of a MNF heated from below and under alternating magnetic fields. Lange et al. [106] considered the thermomagnetic convection in a horizontal layer of magnetic field subjected to a vertical temperature gradient and a spatially modulated magnetic field. Their investigations revealed that, in contrast to the purely thermal driven system, the nonzero flow field of the initial state was characterized by a 2-vortex structure. They also stated that the later state was unknown in the classical Rayleigh–Bénard configuration, and showed a potential of spatial modulations of the external driving to open new horizons in the field of pattern formation with soft magnetic substances. Engler et al. [109] conducted theoretical and experimental investigations on the onset of convection under the influence of time-modulated magnetic field. The shift in the onset of convection depended on the frequency of the external magnetic field. Matura et al. [108] investigated the influence of a time-periodic and spatially homogeneous magnetic field on the linear stability properties and on the nonlinear response of a ferrofluid layer heated from below and above. They observed that the stability of the conductive state and particularly the type of response, which can be harmonic or sub-harmonic, was determined by the system parameters. The stability boundary of the conductive state in the high-frequency limit coincided with the stationary stability boundary when a mean magnetic Rayleigh number was used. The stability boundary for low-frequency modulation was shifted in a way that the conductive state got stabilized. They noted that sub-harmonic response was not typical for ferrofluids because of their high Prandtl numbers. However, in low-Prandtl number simulations, they found nonlinear relaxed sub-harmonic convective states as predicted by the linear analysis. They further investigated the nonlinear response for heating from below and above for a large span of modulation frequencies. For a high-frequency modulation, the dynamics was nearly averaged, and the order parameters approach the values, which have a driving with the corresponding mean magnetic Rayleigh number. In the case of heating from above, a change in the sense of rotation of the convection rolls was observed. They also noted that, for a low-frequency modulation, the numerical noise could affect the pattern selection. This was the

case when the convection amplitudes cannot be below the noise level, depending on the numerical accuracy, in the under-critical phase of driving. The simulations showed that for rather low modulation frequencies the oscillation profiles approach the stationary curves.

5. Applications

MNF can be used as a coolant (thermal management applications) and/or a heat transfer medium in energy conversion systems. The later application is in the embryonic stage. The use of MNF in thermal management is currently used in some commercial applications such as loud speakers cooling [21]. The most recently developed applications will be reviewed as follows.

5.1. Energy convention devices

Shimada [110] analyzed the flow and heat transfer characteristics in a parallel duct-type energy conversion device with a MNF under a non-uniform magnetic field using the theoretical equations based on the heat conduction theory. The results showed that the heat conduction model was capable of predicting the temperature and pressure distributions quantitatively for the performance of various types of magnetic field. Lian et al. [111] established a mathematical model for the prediction of flow and heat transport features of the temperature-sensitive magnetic fluid and the design of an automatic energy transport device based on the thermomagnetic effect. Their results revealed that a stable circulation flow could be maintained in a loop-shape channel in the presence of a proper external magnetic field and temperature gradient of the magnetic fluid. In addition, some studies on the factors affecting the device performance, the magnetic field strength and the fluid temperature difference between the heating section and cooling section were preponderant. It was indicated that the developed device was not sufficiently adequate to be used for heat-to-power energy conversion, and it could be rather used as an automatically-cooling. The developed model was validated with the experimental data. The established model could be used to simulate the performance of devices exploiting the thermomagnetic effect for the design and evaluation purposes. Lian et al. [112] reported the performance of automatic energy transport in cooling devices based on the thermomagnetic effect of a temperature sensitive magnetic nanofluid. The investigated devices consisted of ordered loop of permanent magnets, heat sources, heat sinks and temperature sensitive magnetic fluid assembled into an automatic energy transport device. By adjusting the external magnetic field and/or temperature gradient field inside the magnetic nanofluid, they could control the energy transport process of designed devices. In addition, the constructed device showed a self regulating feature that the flow velocity of the MNF increased with the increase of the heat load and vice versa. Their results also showed that the performance of automatic energy transport systems was related to the structure of constructed loop.

5.2. Thermomagnetic convection based cooling

The thermomagnetic convection based on cooling is one of the thermal applications of MNF. As mentioned above, the application of an external magnetic field on a MNF with varying susceptibilities gives a non-uniform magnetic body force (i.e., Kelvin body force), which leads to the thermomagnetic convection. Since most of MNFs exhibit a superparamagnetic behavior, they do not obey the Curie–Weiss law, thus becoming less magnetic at higher temperatures. Recent development of thermomagnetic cooling devices is mainly motivated by their great potential application for small scale cooling devices such as in miniature micro-scale electronic devices.

Zablotsky et al. [90] investigated a possibility of technical application of surface cooling based on thermomagnetic convection. They found that the cooling effect of 75 W/cm^2 reached in their setup could meet only low technical demands. Their results also confirmed that that a significant augment of the cooling intensity by thermomagnetic convection could be obtained only in a case if the heat source was located into the region of a maximal magnetic field intensity, when the efficiency of power generation cycle reached its maximum. A high intensification of the heat transfer observed when the magnet was placed in proximity of the warmer source was in agreement with the previous studies by Rosensweig [113] and Jue [114]. Li et al. [115] reported the operating characteristics of a miniature automatic cooling device at different parameters. They found that for the design of a cooling device with a MNF as a coolant, the following points should be concerned:

i. To select a suitable magnetic fluid with a greater pyromagnetic coefficient, a lower Curie point, a higher saturation magnetization, a lower viscosity and a higher boiling point;
ii. To exert a stronger intensity of the external magnetic field and/or the field gradient, if possible; in order to maintain a synergy between the magnetic field and the temperature gradient field.

Xuan et al. [116] reported the practical design of a liquid cooling device based on the thermomagnetic effect for electronic cooling, in which the waste heat generated from the electronic elements was used as a useful power to drive the magnetic fluid flow and to transport the waste heat to a distant radiator. They found that the thermomagnetic cooler with a magnet located nearby the heat source could realize a better cooling performance and a steadier start-up procedure. They also emphasized on the advantages and disadvantages of thermomagnetic cooling for electronic cooling applications.

5.3. Thermal conduction based and smart cooling

A recent work demonstrated that the thermal conductivity of MNF could be tuned by an externally applied magnetic field [22]. These findings, developed at the India Gandhi Center of Atomic Research, were used in development of “smart” cooling devices that took advantage of the large thermal conductivity enhancement and the conduction to remove the heat from a hot device immersed in MNF. Philip et al. [53] developed a multifunctional device that used MNF with tunable thermal conductivity to viscosity ratio to remove heat and arrested vibrations (damper), simultaneously. They concerned that the development of such devices could have applications in micro-fluidic devices, micro- and nano-electromechanical systems (MEMS and NEMS) and other miniature devices. However, these thermal conductivity based cooling devices are still in their embryonic stage and need a further development for practical applications.

6. Concluding remarks and future directions

This paper reviewed recent development on MNF for heat transfer applications. Recent studies have dominated the thermomagnetic convection and the development of devices by means of thermomagnetic effects. Some researchers initiated the investigations on other aspects of heat transfer such as the enhancement and control of thermal conductivity of MNF in the presence of an external magnetic field. The use of MNF in heat

transfer applications appears promising. However, the development of this area is still challenged by many aspects ranging from the preparation and characterization of MNF to practical applications through the understanding of the mechanisms responsible for the observed heat transfer enhancement. In order to design systems with enhanced heat transfer and/or heat transfer effectiveness (heat transfer coefficient) using a MNF as a heat transfer fluid, the understanding of the mechanisms and the physical phenomena is needed. The problems of hydrodynamics and heat/mass transfer have been dealt with. However, some problems related to the stability of MNF in the presence of magnetic and gravitational fields, heat transfer mechanisms and the influence of formulation methods on the thermophysical properties are still needed to be solved.

Recent studies on MNF preparation mainly focused on the preparation of temperature sensitive *super-paramagnetic* nanoparticles and their dispersion in appropriate carrier fluids. In an ideal MNF, each particle appears superparamagnetic with the magnetic moment $\vec{m}$. However, a real MNF, as used in some experiments, is a poly-dispersed system and may contain a small fraction of single- and/or multi-domain ferro-/ferri-magnetic nanoparticles. The presence of these coarser particles could lead to a poor stability of MNF and have severe effects on the thermophysical properties of the fluid and the heat transfer effectiveness of systems as well. In addition, the coarser particles in the MNF samples in the presence of magnetic field lead to the formation of long and irreversible chain-like clusters, which have detrimental effects on the thermophysical properties (such as thermal conductivity and viscosity) of the fluid. A higher thermal conductivity could be expected for MNF prepared with the smaller particles. It was interesting to note that the polydispersity of magnetic nanoparticles could also affect directly the current of thermomagnetic convection. Future investigations on the preparation of MNF should focus on the control of size/size distribution of magnetic nanoparticles. Another aspect for further development is the particle morphology control during the preparation. It is well known that the magnetic properties of magnetic nanoparticles and hence the cluster formation in magnetic nanofluids could be affected by the particle morphology. The control of particle size/size distribution together with the particle morphology may lead to the preparation of well-engineered MNF with desired properties and long-term stability and further on the development of devices using MNF for practical applications.

Some studies have shown that the thermal conductivity increased with the particle volume fraction in the absence of magnetic field. It is clear that the intensive investigations are needed to understand the mechanisms and the influence of other parameters (such as surfactant layer, particle morphology, temperature, etc.) on the thermal conductivity of MNF in zero magnetic fields.

The investigations on thermal conduction in the presence of magnetic field have shown a promising and potential application in various fields such as smart cooling. The anomalous thermal conductivity observed was explained by the formation of chain-like structures in MNF under the magnetic field. The understanding of these structures and their manipulation by an external magnetic field becomes the main challenge of the future investigation on thermal conductivity enhancement in MNF. The control of the self-assembly processes requires the understanding of the relationship between the magnetic properties and other particle characteristics such as particle size/size distribution, particle morphology as well as the applied magnetic field. The future investigations on thermal conductivity enhancement in the presence of magnetic field should focus on the following aspects:

a) understanding of the interplay among the parameters such as particle size/size distribution, particle morphology and coating shell and external magnetic field as well as its influence on particle clustering in MNF;
b) development of thermal conductivity models based on particle clustering, clusters morphology and distribution;
c) understanding and optimization of the synergic effect of thermal conductivity and viscosity of MNF in the presence of magnetic field;
d) development of the thermal conductivity and viscosity of MNF with magnetic nanoparticles-carbon nanotube composites, or other novel materials; and
e) development of cooling based devices and the potential application of the thermal conductivity tuning in energy conversion systems and heat exchangers.

The thermomagnetic convection received a particular attention, and the results on the corresponding numerical simulations and modeling are shown in the literature. Future investigation should focus on the experimental validation of the existing models. In addition, the temperature-sensitive magnetic nanofluid where the thermomagnetic convection is mainly enhanced through the pyromagnetic coefficient is investigated. However, recent studies have shown that the thermomagnetic convection could be strongly affected by the magnetoviscous effect as well as the magnetic field effect. In future, this aspect should be also investigated for both temperature sensitive magnetic nanofluids and magnetite-based nanofluids. Another aspect for further development is the thermomagnetic convection affected by modulated magnetic fields.

It was demonstrated that the solar radiation could be completely absorbed in a magnetic nanofluid layer with about 10-mm thickness [117]. This offers a possibility of using MNF as a heat transfer medium in solar installations. However, studies regarding the parameter effects on the overall heat transfer coefficient and the fluid flow within the system still are needed. Future work should focus on the investigation on the optical and thermal properties of MNF as well as their possible influence on the performance of solar collectors, especially in the case of direct absorbing solar collectors. Another interesting aspect may be a possible design of solar thermosyphons where the fluid flow and heat transfer process may be completely controlled by an external magnetic field.

The use of MNF for heat transfer enhancement is promising. This field has made a significant progress for some challenging applications such as smart cooling, automatic energy devices, automatic cooling devices, etc. However, it is still on the way to go before some novel devices using MNF as a heat transfer medium may satisfy the practical applications.

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